Model simulations of continuous ion injection into electron-beam ion source trap with slanted electrostatic mirror[a)]

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The efficiency of trapping ions in an electron-beam ion source (EBIS) is of primary importance for many applications requiring operations with externally produced ions: RIA breeders, ion sources, and traps. At the present time, the most popular method of ion injection is pulsed injection, when short bunches of ions get trapped in a longitudinal trap while traversing the trap region. Continuous trapping is a challenge for EBIS devices because mechanisms which reduce the longitudinal ion energy per charge in a trap (cooling with residual gas, energy exchange with other ions, and ionization) are not very effective, and accumulation of ions is slow. A possible approach to increase trapping efficiency is to slant the mirror at the end of the trap which is opposite to the injection end. A slanted mirror will convert longitudinal motion of ions into transverse motion, and, by reducing their longitudinal velocity, prevent these ions from escaping the trap on their way out. The trade-off for the increased trapping efficiency this way is an increase in the initial transverse energy of the accumulated ions. The slanted mirror can be realized if the ends of two adjacent electrodes, drift tubes, which act as an electrostatic mirror, are machined to produce a slanted gap, rather than an upright one. Applying different voltages to these electrodes will produce a slanted mirror. The results of two-dimensional (2D) and three-dimensional (3D) computer simulations of the ion injection into an EBIS are presented using simplified models of an EBIS with conical (2D simulations) and slanted (3D simulations) mirror electrodes. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2828061]

I. INTRODUCTION

The first ion injection into cryogenic electron beam ion source from the external ion source has been done in Saclay by Faure *et al.*[1] and later developed by this group on DIONE electron-beam ion source (EBIS).[2–4] The most popular method of injecting the externally produced ions into EBIS trap is a fast potential trapping. With one axial potential barrier on the side opposite the injection end the ions from an external source are traversing the trap region and escape in the direction they came from. At a time when the trap region is filled with traversing ions, the second barrier on the side of injection is raised and ions between two axial barriers are trapped. In the radial direction, these ions are confined by the electric field of the electron beam space charge. Since the maximum number of trapped ions with this method is limited to the number of ions traversing the trap region, the injection of light ions in a multiampere electron beam becomes problematic. When using the alternative method of "slow" ion injection, the potential distribution on the drift tubes is the same as for the ion confinement with pulsed method: the potential barriers on both sides of the trap region are "on." The injection time of slow ion injection is not limited to the ion traversing time. To capture ions coming into the trap from the external source, this method utilizes mechanisms, which reduce the ion longitudinal energy per charge during their traversing the trap region (ionization, energy loss in ion-ion, and ion-molecule interactions). Since the probabilities of these processes during the traversing time are small, the injection of sufficient number of ions can take time comparable or longer than the necessary ionization time. The

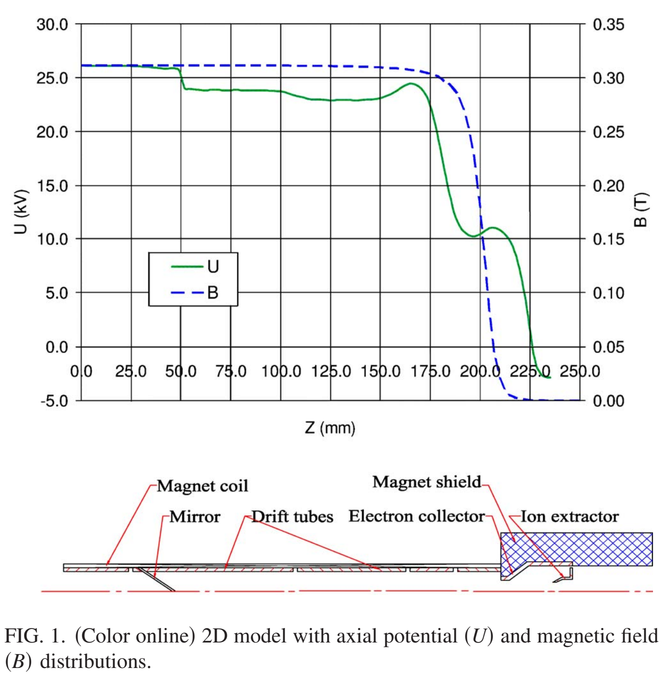

FIG. 1. (Color online) 2D model with axial potential (U) and magnetic field (B) distributions.

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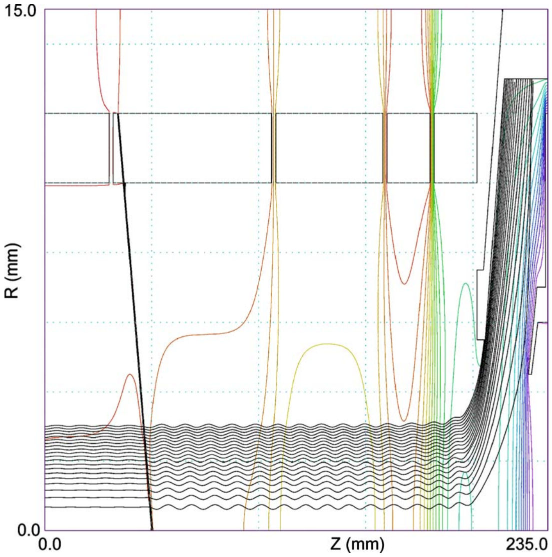

FIG. 2. (Color online) Simulated electron beam transmission in 2D model of ion trap with conical mirror.

charge state spectrum in this case will have a low-charge state tail typical for continuous injection from gas in a trap region.

II. CONCEPT OF ION INJECTION WITH SLANTED ELECTROSTATIC MIRROR

Potential trap of EBIS is created by the electron beam space charge providing radial confinement of positive ions and by two axial potential barriers on both sides of the ion trap to prevent ions from leaving the trap axially. With continuous external ion injection, the axial barrier on the injection side of the trap (first barrier) has to be lower, so that ions which passed this barrier will be reflected from the second one (second barrier) on the opposite side of the trap.

To prevent ions which are traversing the trap region from leaving the trap, the axial component of kinetic energy per charge needs to be reduced during their travel between two barriers. This can be done by transferring part of the longitudinal energy component into transverse component (radial and azimuthal) when the ion is reflected by an electric field which is not parallel to the axis of ion motion. The simplest configuration of electrodes generating such inclined electric field would be two adjacent cylindrical electrodes with facing parallel edges cut at an angle different from 90° with respect to the axis. Some ions reflected from such slanted electrostatic mirror will lose some of their longitudinal component of energy and will be trapped. Their transverse energy will increase, but as long as the radial energy gain does not exceed the potential difference between the original maximum radius of its oscillations and the wall, this ion will not hit the wall and will stay in a trap region. The other ions will increase their longitudinal component of energy and will leave the trap region. Whether the ion will be trapped or reflected back from the second barrier and lost will depend on the angle between vector of the ion's velocity and the normal to the reflecting equipotential surface. Ions hitting the reflecting equipotential surface of the slanted mirror with angle smaller than the angle between the axis and normal to this surface will increase their transfer energy and will be trapped. The ions with larger angle of impact will gain axial energy component and will be lost. Based on this simplified model, one would expect the slanted mirror to be more effective in a region of the trap with the largest average ratio of longitudinal to transverse energies where the angle of impact is minimal.

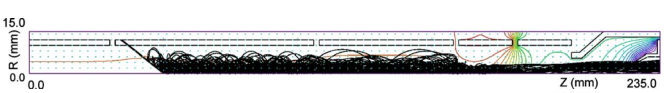

FIG. 3. (Color online) Simulated ion trajectories with active slanted mirror 45°.

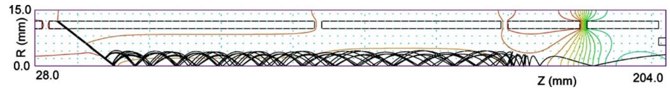

FIG. 4. (Color online) Simulated trajectory of a single ion trapped between two barriers.

III. TWO-DIMENSIONAL SIMULATIONS

For both two-dimensional (2D) and three-dimensional (3D) simulations, the electron current was $i_{el}=5.0$ A, electron energy $E_{el}=25.0$ keV, electron beam radius $r_{el}=3.0$ mm, inner radius of drift tubes $r_t=10.0$ mm, and magnetic field in the trap region $B=0.3$ T. The injected monoenergetic ion beam had radius $r_{ion}=4.0$ mm with zero emittance, zero divergence and zero current. 2D simulations have been done with program TRAK.[5] Because of limitations of the 2D program with cylindrical symmetry, the model of asymmetric slanted mirror was substituted with model of symmetrical conical mirror consisting of two concentric cones transparent for particles. The number of electrons was 100 and number of ions was also 100.

The 2D model in R-Z coordinates with potential and magnetic field distributions is presented in Fig. 1.

The electron beam transmission through this structure is presented in Fig. 2.

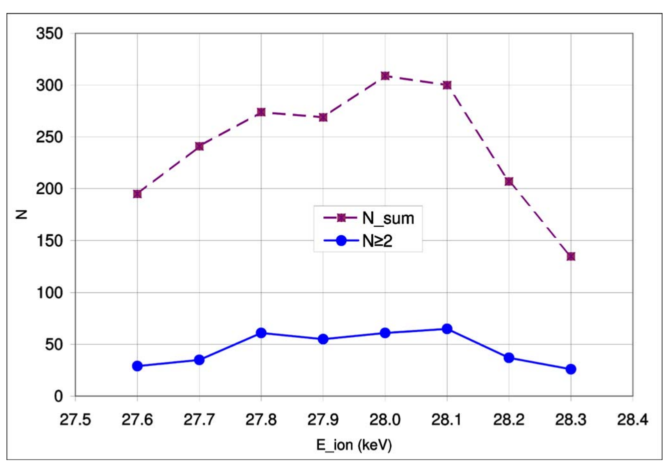

FIG. 5. (Color online) Ion trapping statistics for 2D model of conical mirror with angle 45°. $N \geq 2$ is the number of ions with two or more reflections N_sum is the sum of products of number of reflections times number of ions which made these reflections.

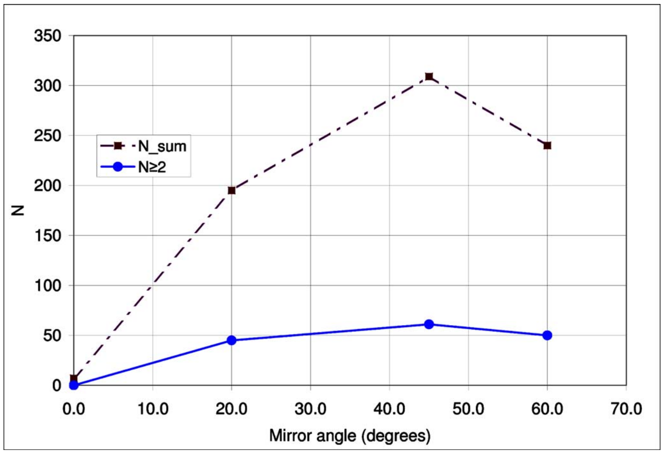

FIG. 6. (Color online) Dependence of maximum number of trapped ions on the angle between mirror cut plane and axis for a fixed voltage between mirror electrodes 2.4 kV (2D model).

With magnetic field of 0.3 T, the effect of slanted mirror on the electron beam transmission is relatively small. Without axial barriers, the ions injected into electron beam are passing through the trap region, and none of them get trapped. With both axial barriers in place the conical mirror becomes active and ion energy transfer and therefore ion accumulation takes place. The simulated ion trajectories with trapping potential distribution on the drift tubes are presented in Fig. 3. The mirror angle is defined as an angle between longitudinal axis and a plane of cut the mirror electrode.

One can see that in a process of ion accumulation, the diameter of ion system in a trap increases because in this model, the trapped ions get reflected outward and they increase their transverse energy. The trajectory of a single trapped ion oscillating between two potential barriers is presented in Fig. 4.

This ion makes nine reflections in a trap, it did not come out of the trap and did not hit the wall.

The results of 2D simulations for a slanted mirror angle of 45° are presented in Fig. 5.

The maximum number of ions with more than two reflections reaches 61 out of 100. The upper curve shows a gain in number of ions in a trap because of trapping ($\Sigma[N_i \cdot i]$, N_i is the number of ions with i reflections). Considering that number of ions entering the trap region is usually less than 100 because of reflection the peripheral ions from the first barrier this gain is seen as substantial. The width of curves ($N \geqslant 2$) and (N_sum) is approximately 500 eV, which corresponds to the radial potential well within electron beam area populated with ions. From Fig. 6, one can see that accumulation of ions in 2D model for the existing conditions in a trap has maximum at 45°.

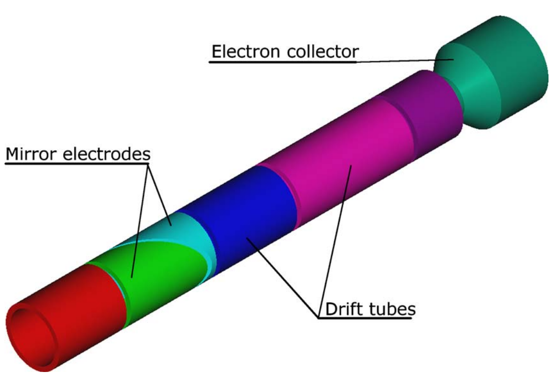

FIG. 7. (Color online) 3D model of the ion trap with slanted mirror.

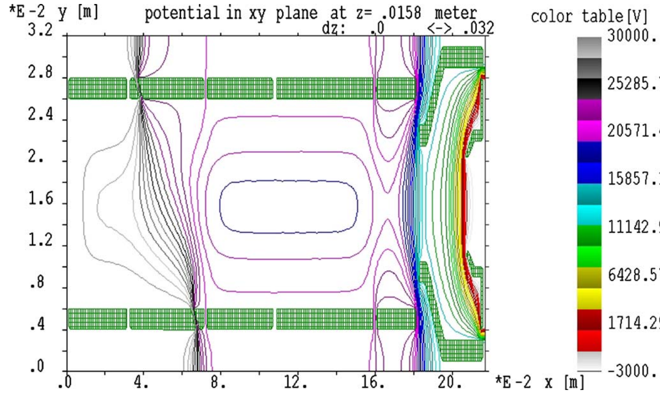

FIG. 8. (Color online) Electrostatic field map with electron beam space charge for 3D model of the ion trap with slanted electrostatic mirror (mirror angle 20°).

IV. 3D SIMULATIONS

For 3D simulation, we used program KOBRA3-INP.[6] A model for 3D simulations is presented in Fig. 7.

The picture of electrostatic field map with electron beam space charge in this 3D model is presented in Fig. 8.

The results of simulations for different slanted angles of the mirror are presented in Fig. 9.

The trapping efficiency here is defined as a ratio of number of ions, which made two and more reflections in a trap to the total number of ions entering the EBIS model. One can see a strong dependence of ion trapping efficiency on the mirror angle and also on ion energy. As expected with mirror angle equal 90°. The half width of the 60° curve approximately corresponds to 500 eV, which is close to 2D simulation results.

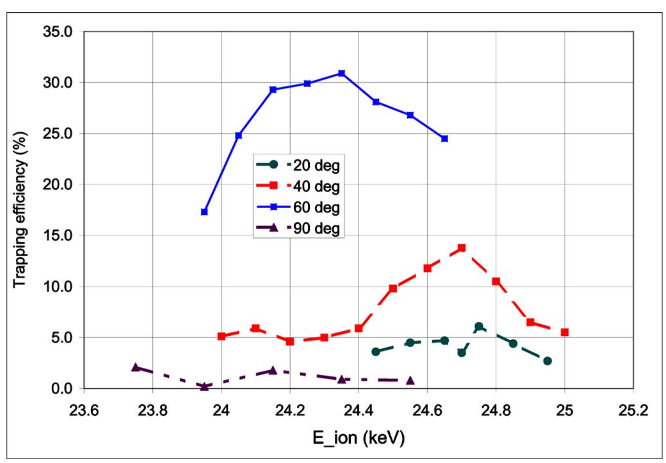

FIG. 9. (Color online) Dependence of ion trapping efficiency on ion energy for different mirror angles (3D model). The voltage difference between the mirror electrodes was fixed at 3.0 kV.

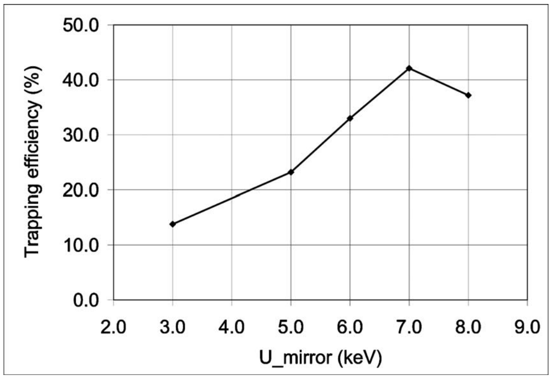

FIG. 10. Dependence of trapping efficiency on the voltage difference between mirror electrodes for a fixed mirror angle 40°.

Since the voltage between mirror electrodes determines the position and shape of the reflecting equipotential, an attempt was made to simulate the dependence of trapping efficiency on the voltage difference between adjacent mirror electrodes.

As one can see from Fig. 10, this voltage has strong effect on the efficiency possibly because of effectively changing the angle of the reflecting equipotential in the ion reflection region. As an alternative method of controlling this angle, it is possible to build a mirror not of two electrodes but of three or more with additional wedge-shaped electrodes in a gap between side electrodes. Such geometry of electrodes allows varying the mirror angle in a wider range than just by changing the voltage between mirror electrodes.

V. CONCLUSION

With all quantitative differences in simulations with 2D and 3D programs, it was demonstrated that, at certain conditions, the continuous trapping of ions traversing the EBIS trap by transferring part of longitudinal energy into transverse with slanted electrostatic mirror is possible, and the trapping efficiency exceeds 30%. The efficiency of ion trapping depends on the angle of the mirror with beam axis, probably having maximum in a range 45°–60°. Adjustment of this angle seems to be useful to maximize the trapping efficiency.

ACKNOWLEDGMENTS

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